Imperial College London

Department of AERONAUTICS

DMT Project – Wind Turbine

By Group 23

Our Group

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Hours Spent in Workshop

Alanis Dos Santos - 12h

Anjali Jaghra - 15h

Aishaani Jha - 15h

Justine Knopf - 15h

Connor Maclennan - 15h

Lothaire Valex - 15h

Summary of Main Technical Aspects

Number of Blades	Rotor Diameter (mm)	Aerofoils	Construction Methods	Materials	Adhesives	Surface Finish	Estimated Cost (£)
2	49.95	SG6040 & SG6043	Laser cutting & 3D printing	Plywood & Tough PLA filament	Wood Glue & Epoxy	Varnish	25

Blade Assembly Drawing

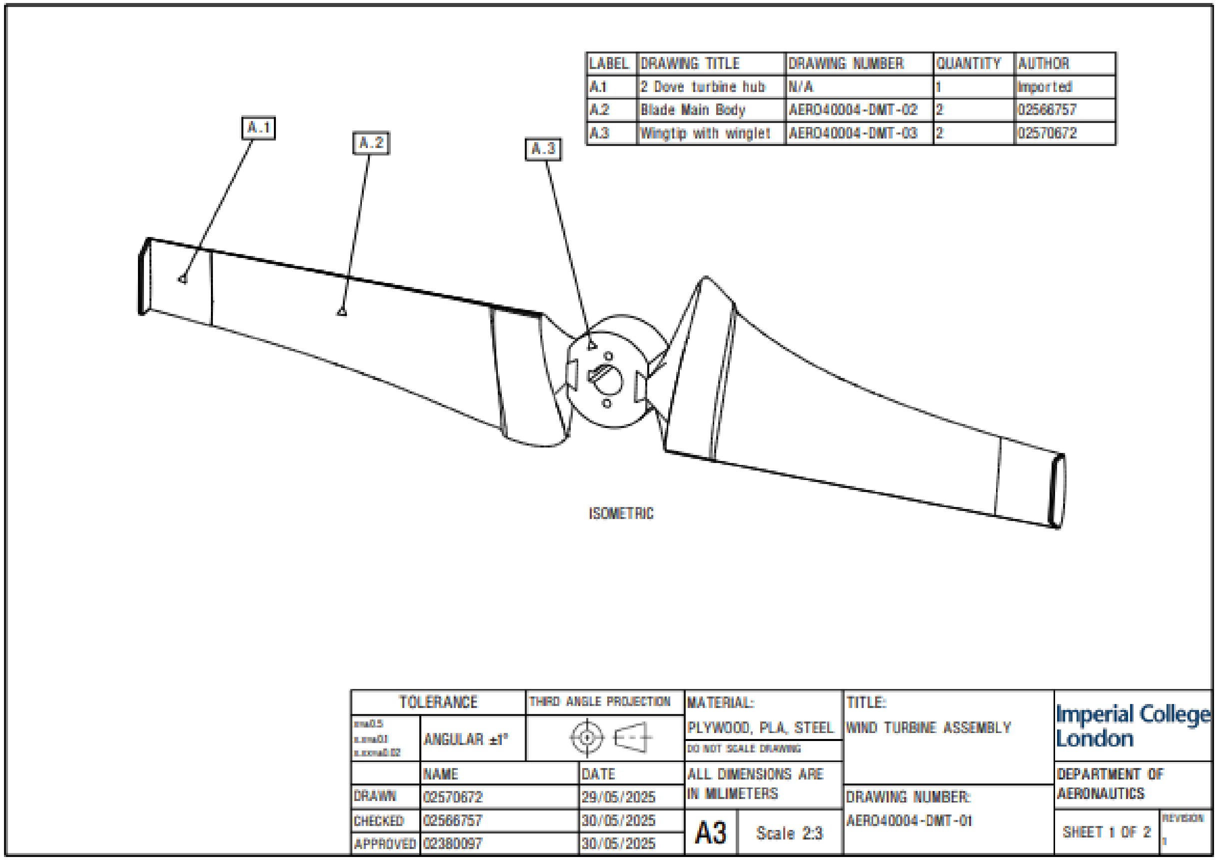


Figure 1: Blade Assembly Drawing

Final Product

Figure 2: Final version of blades

Contents:

Overall Design Methodology

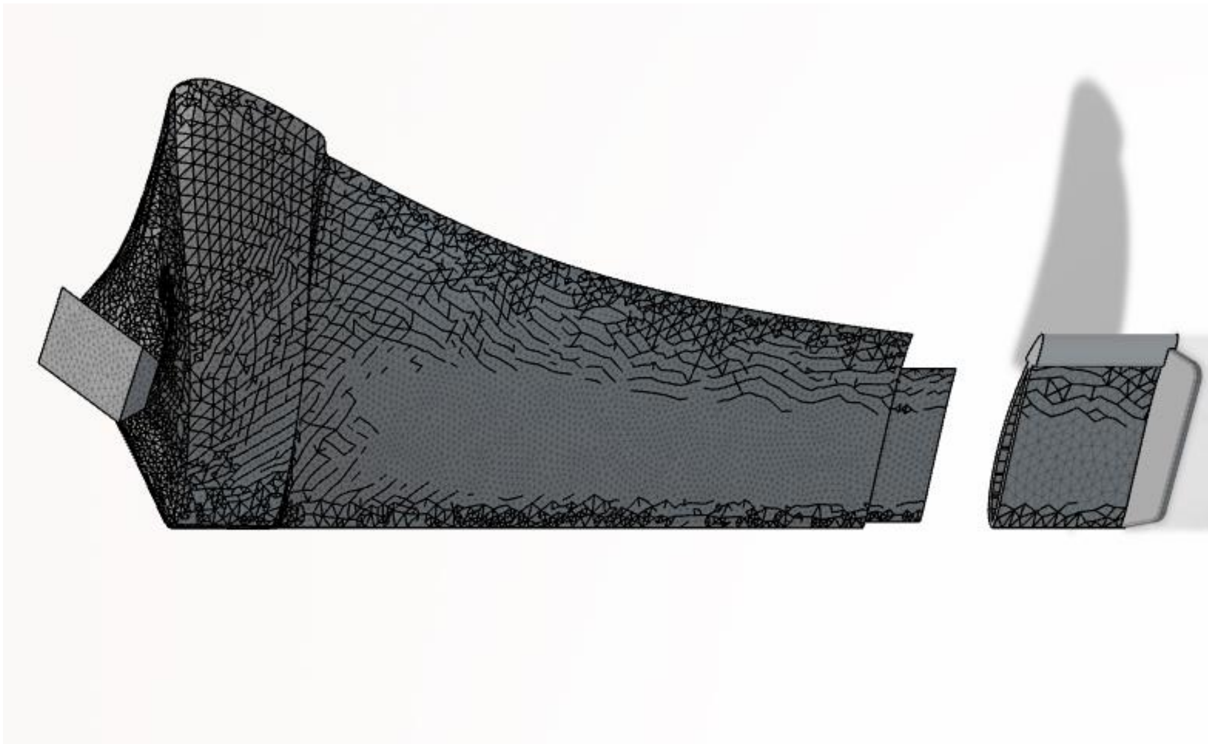


Figure 3: Exploded view of the full blade

Overall Design Methodology

Chosen airfoils:

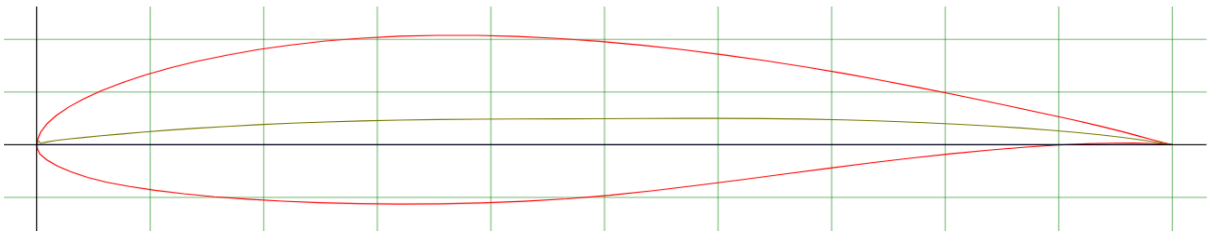


Figure 4(a): SG6040 (via Airfoil Tools)

Figure 4(b): SG6043 (via Airfoil Tools)

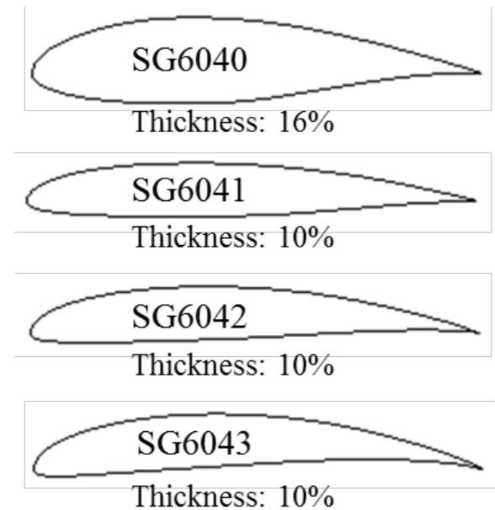


Figure 4(c): SG604x profile (1)

Overall Design Methodology

Our way of maximizing performance - **winglets**

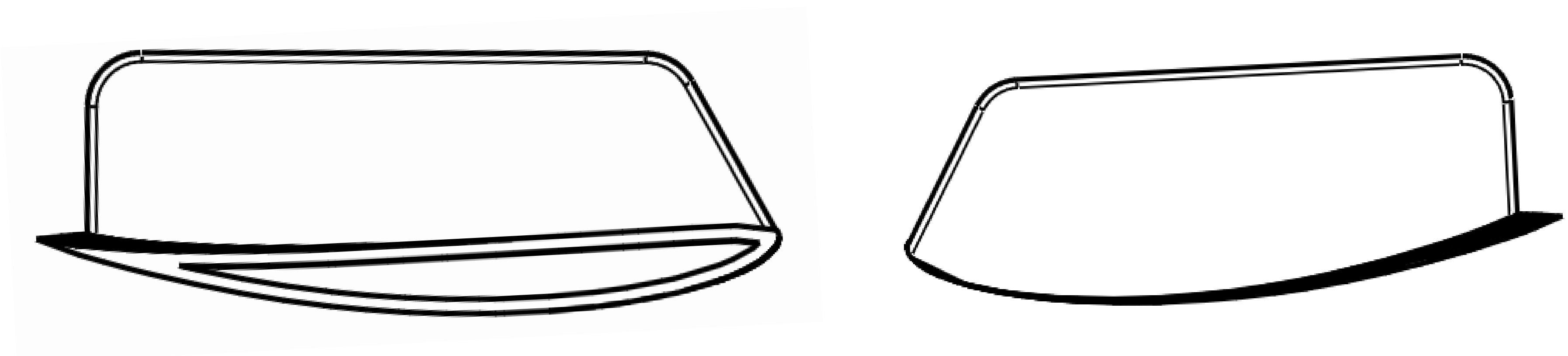
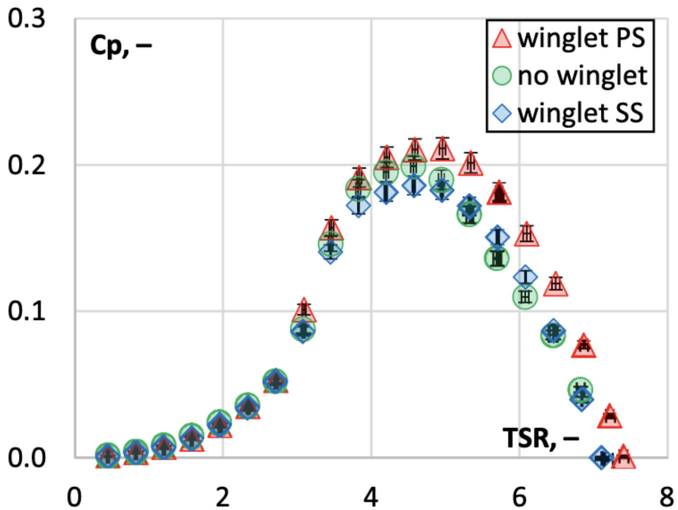


Figure 5: Orthogonal views of the wing tip

Overall Design Methodology



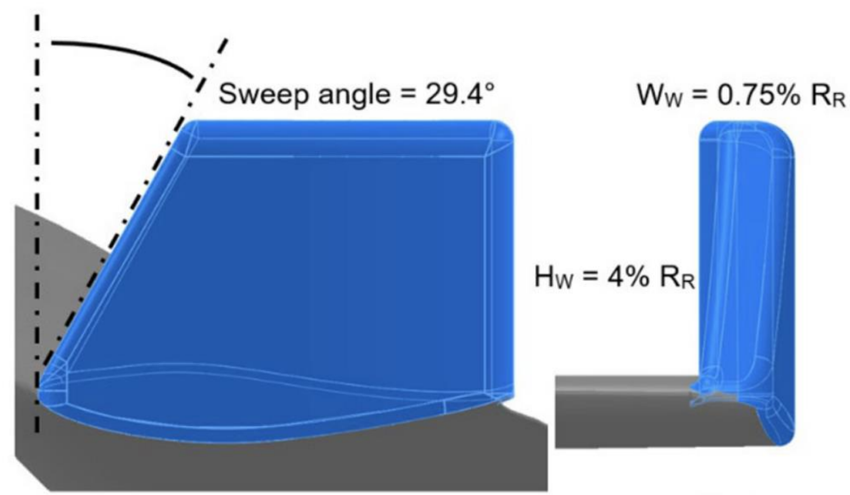


Figure 6(a): Coefficient of power against varying Tip Speed ratio, experimental data (6)

Figure 6(b): Winglet geometry (6)

Overall Design Methodology

Figure 7(a): Laser cutting layout.

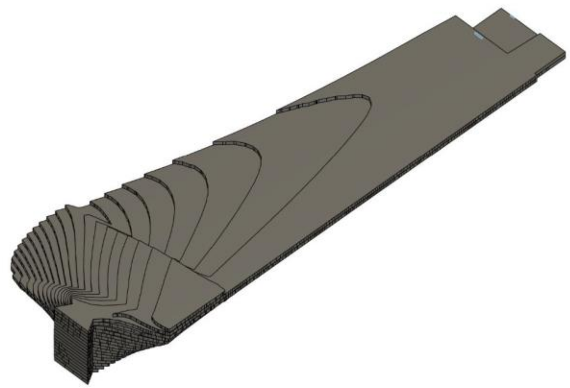


Figure 7(b): Representation of the blades vertically sliced

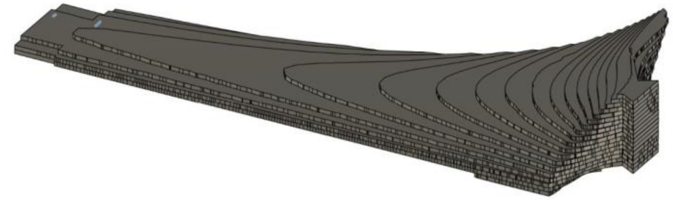


Figure 7(c): Representation of the blades vertically sliced

Overall Design Methodology

Material and Adhesive reasoning:

- We chose to use plywood (10 GPa) over balsa (3 GPa) because it has greater Young's modulus and hardness, while also layering it such to properly use the anisotropic nature to minimise breakage
- Using tough PLA for our tip/winglet means it is less likely to break due to PLA being stiff.
- Wood glue between plywood sections was chosen because it creates strong bonds and help distribute stress evenly.
- Epoxy between the PLA section and the tip of the plywood as it was the most suitable.
- Lastly, we decided on a varnish for the surface finish as it'll make it smooth and more aerodynamically beneficial.

Aerodynamic Performance Prediction

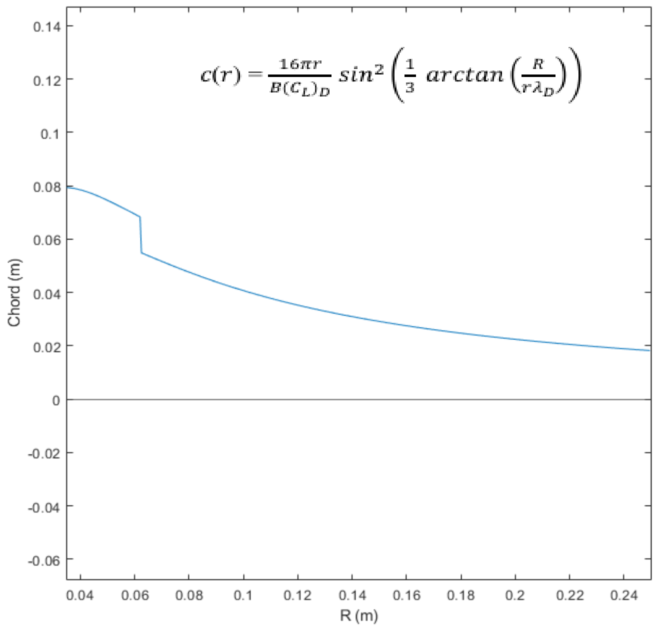


Figure 8(a): Chord against radius, not modified

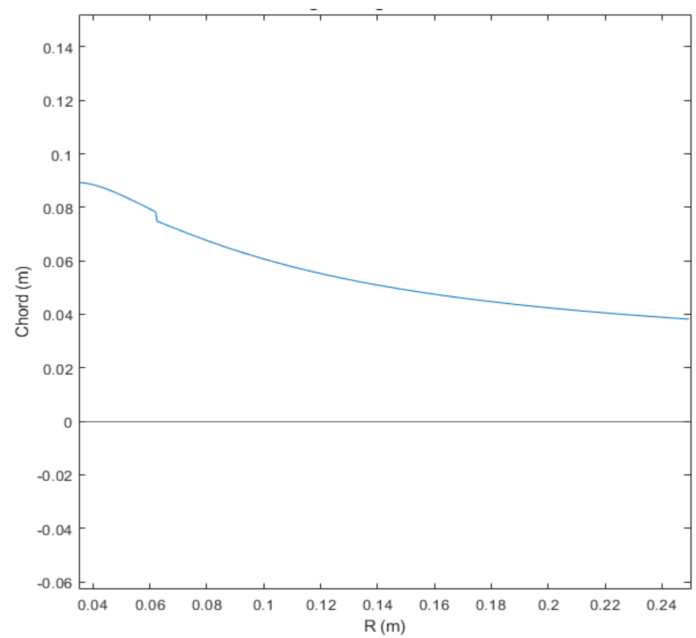


Figure 8(b): Chord against radius; 0.01m added to the chord from start to one quarter of the blade, the rest has a chord increase of 0.02m

Aerodynamic Performance Prediction

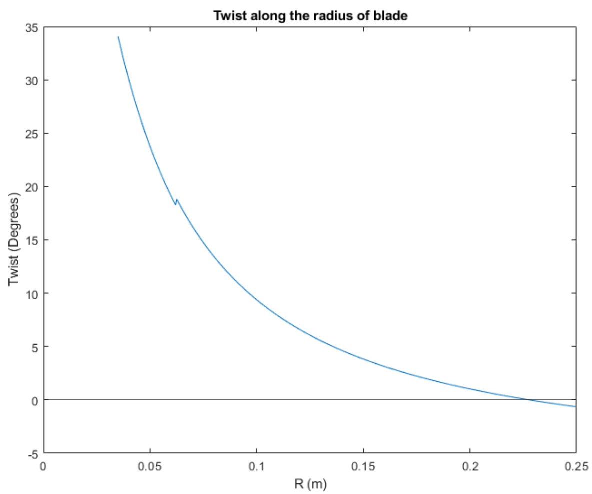


Figure 9(a): Initial twist from BEM optimisation

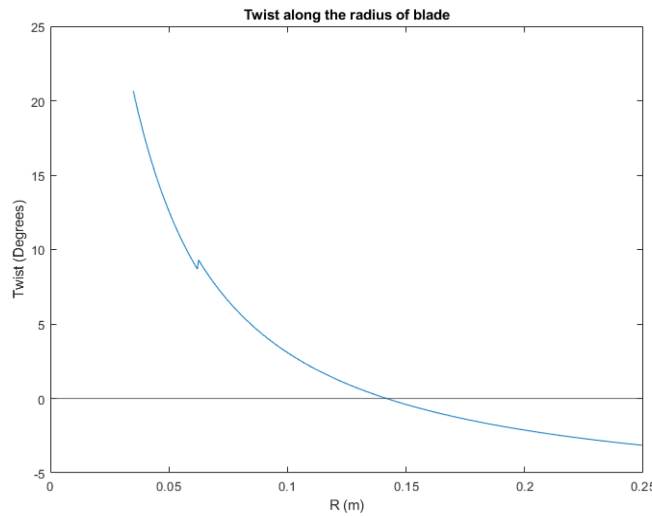


Figure 9(b): Decided twist for blade, based on empirical data and ease of manufacturing

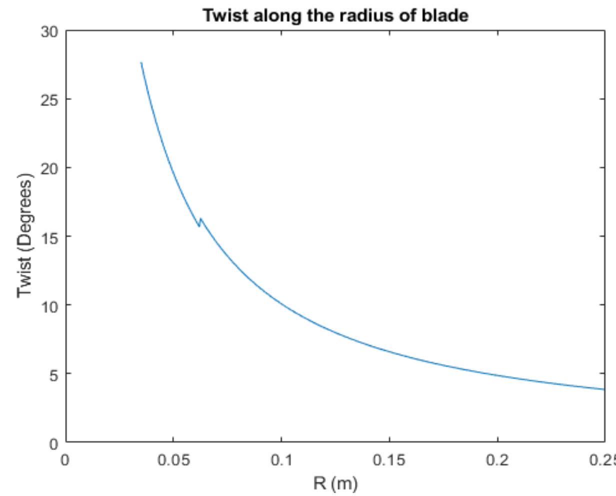


Figure 9(c): Final twist with 7º pitch addition, also based off empirical data

$$\text{Twist} = \arctan\left(\frac{D}{3.55 \cdot r^{1.06} \cdot \lambda}\right) - \alpha$$

Aerodynamic Performance Prediction

Modifications to BEM results

Results of a research paper [7], which are similar to [8]
Specifications: 50cm diameter, 8m/s wind, TSR 5
- Rotor A: BEM optimised chords and twist
- Rotor B: modified chord distribution, tip chord of 3.3cm

Rotor	Predicted C_p	Experimental C_p
A	0.4	0.240
B	0.333	0.335

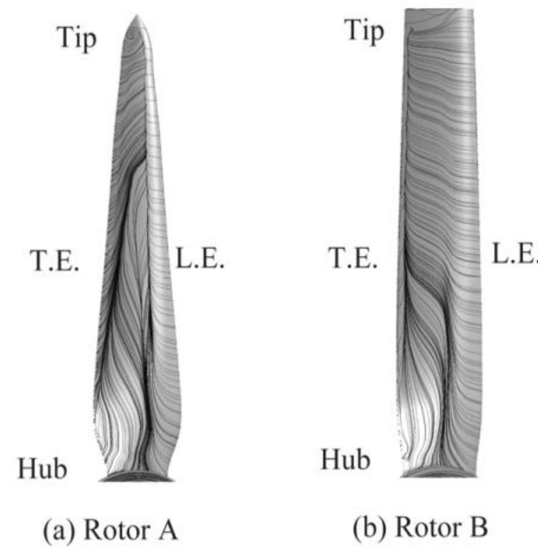
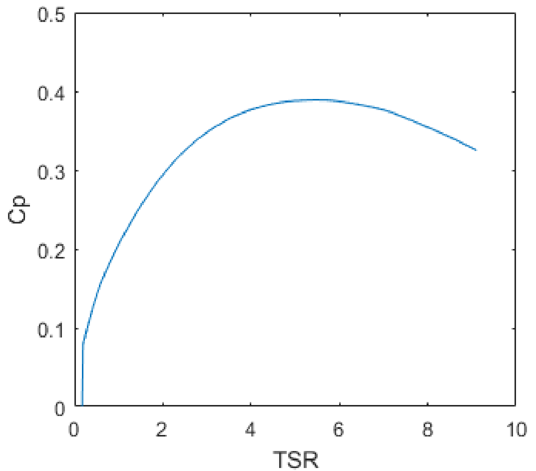
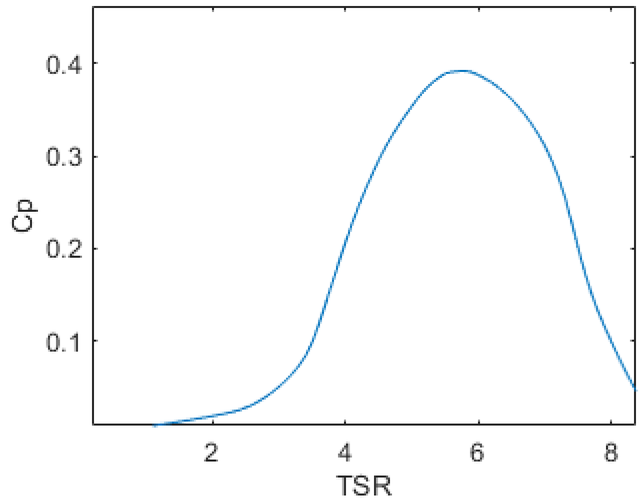


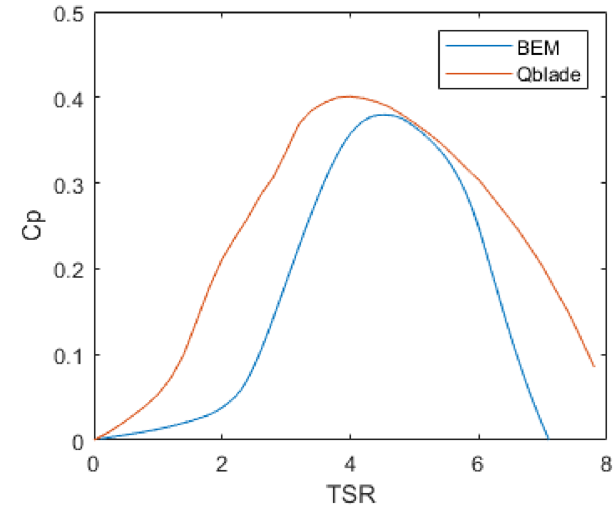
Figure 11: Turbine Blades (8)

--> According to CFD [7], presence flow separation in the mean side in Rotor A, but not for B.
--> L/D curves via interpolation for Re<100k are inaccurate [7]

Aerodynamic Performance Prediction







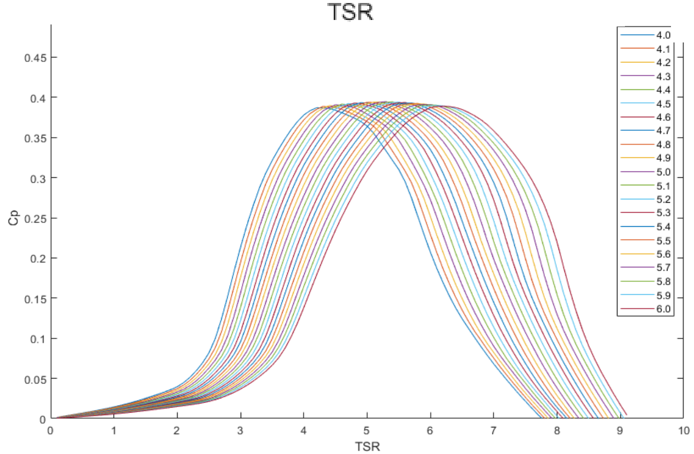


Figure 8(a,b) left: Running for different TSR where the chord and twist change with TSR to find the optimum

Figure 8(c): Coefficient of Power against Tip speed ratio for non-modified twist and chord.

Figure 8(d): Coefficient of Power against Tip Speed Ratio (TSR) for final blade (with modified twist and chord). From BEM and Qblade

Aerodynamic Performance Prediction

The final value for Coefficient of Power: 0.3923 at a TSR of 5.8

This is a 3.35% increase from not having the modification of an additional 7 degrees of pitch and an increased chord length towards the tip. The equations used in finding the dsitributions:

$$\text{Twist} = \arctan\left(\frac{D}{3.55 \cdot r^{1.06} \cdot \lambda}\right) - \alpha \qquad c(r) = \frac{16\pi r}{B(C_L)_D} \sin^2\left(\frac{1}{3} \arctan\left(\frac{R}{r\lambda_D}\right)\right)$$

Power output before modifications: 46.37 W

Power output after modification: 44.87 W

This was found using :

$$\boxed{P = C_p P_{in} = \frac{1}{2} C_P \rho A_t v_1^3}$$

Where ρ was 1.204kg/m^3 and radii 0.25m and v=10m/s

$$F_d = \frac{1}{2}\rho u^2 C_d A$$

Starting torque = Fd * r = 0.09456 Nm

with a Cd = 0.032 at 0 AoA for sg6043

Aerodynamic Performance Prediction

The code to find output power and Coefficient of Power also includes corrections and modifications:

- Inclusion of aerofoil drag forces (10)
- Glauert's optimum rotor, accounting for wake rotation (Euler's turbine equation)(11)
- Tip loss correction: Prandtl's tip loss factor(10)
- Root loss correction(10)
- Stall delay correction(12)

AC refers to SG6043 and AD to SG6040

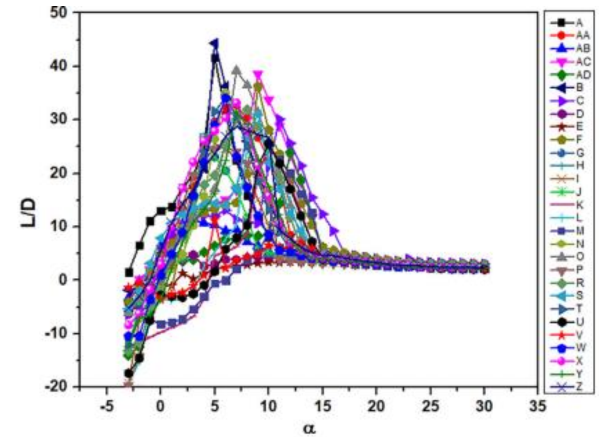


Figure 9(a) above: Lift coefficient against angle of attack at a Reynold's number of 50000 (14)

Figure 9(b) above: Lift against drag at a Reynold's number of 50000 (14)

Figure 9(c) left: Xfoil Cl vs AoA at 50k reynolds

Structural Performance Prediction

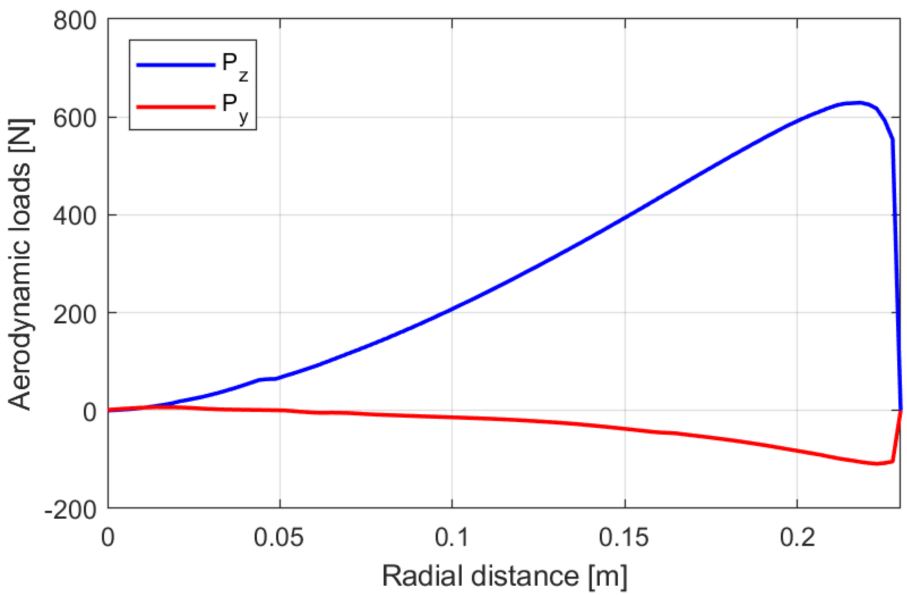
Aerodynamic Loads: [16] at TSR=5, W=10m/s

$$P_z = B\frac{1}{2}\rho W^2 c(C_L \cos \emptyset + C_D \sin \emptyset)$$

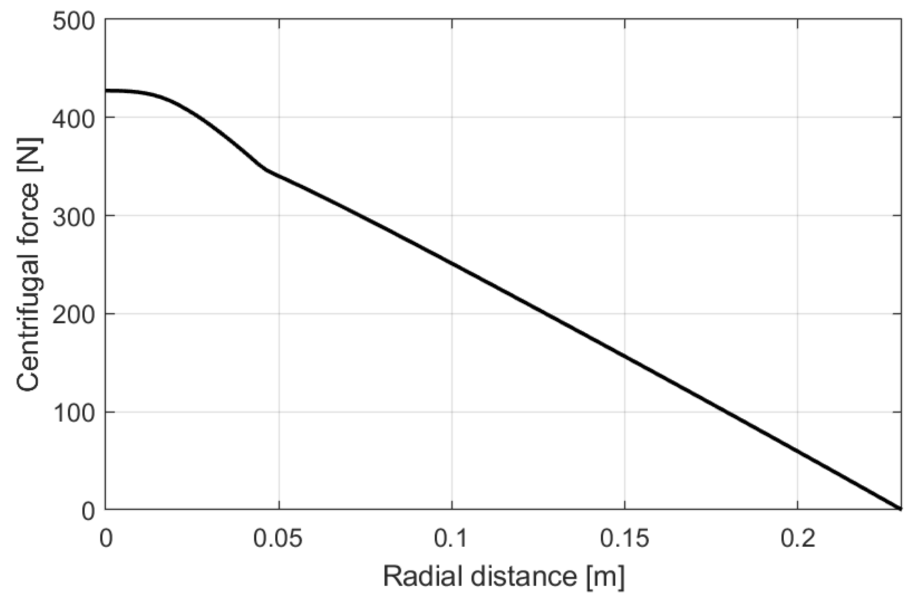
$$P_y = B\frac{1}{2}\rho W^2 c(C_L \sin \emptyset - C_D \cos \emptyset)$$

Centrifugal Loads: [16] at TSR=5, W=10m/s

$$F_r(r) = \rho\Omega^2 \int_r^R A(r')r'dr'$$



Axial and radial aerodynamic loads



Centrifugal Loads at TSR = 8

B: blade number
W: wind speed [m/s]
c: chord length [m]
ρ: air density [kg/m^3]

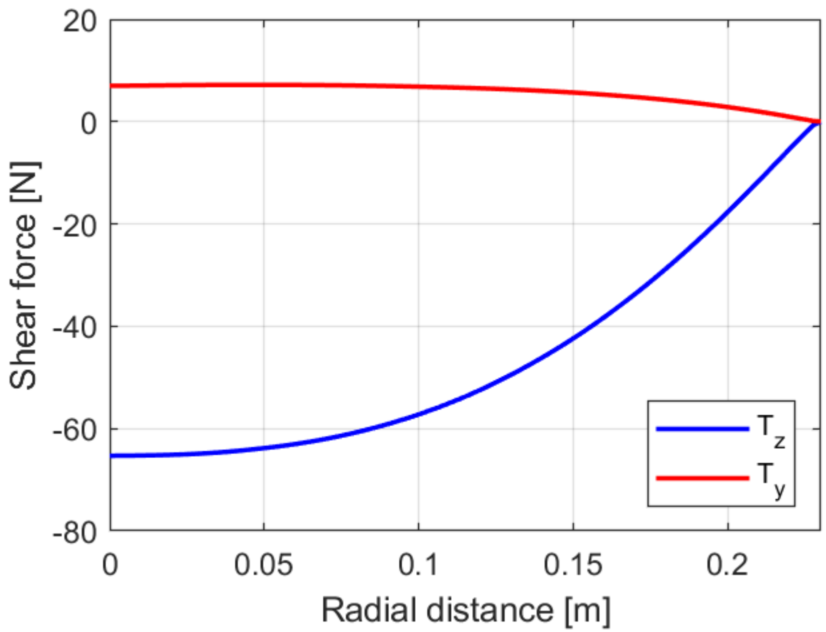
C_L: lift coefficient
C_D: Drag coefficient
ϕ: twist distribution [rad]
Ω: angular velocity [rad/s]

R: lift coefficient
r: Drag coefficient

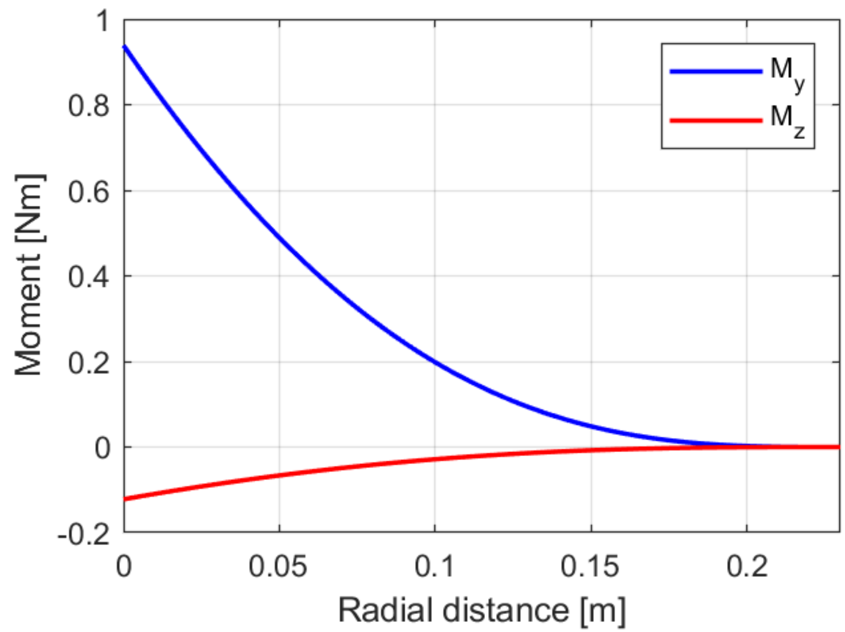
Structural Performance Prediction

Shear forces: $T_z(r) = -\int_R^r p(r')dr'$ [17]

Bending moments: $M_y(r) = \int_R^r T(r')dr'$ [17]



Axial and radial shear force

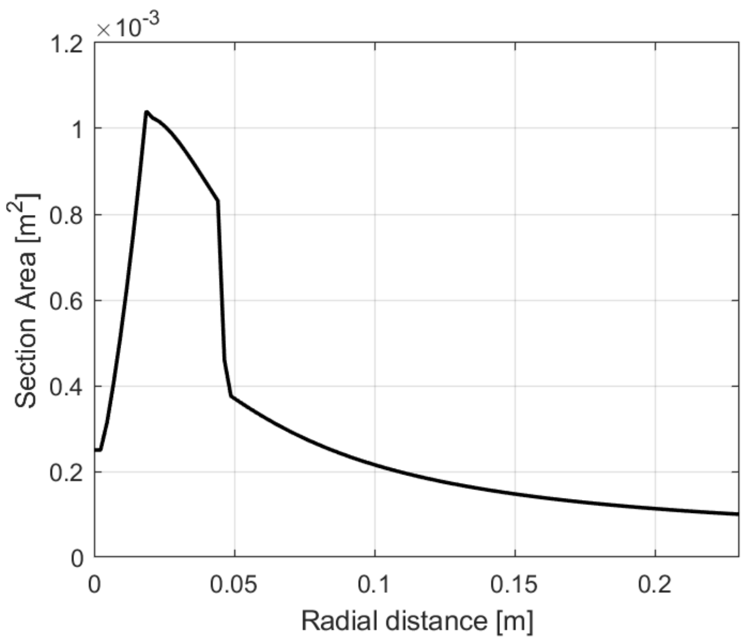


Axial and radial bending moments

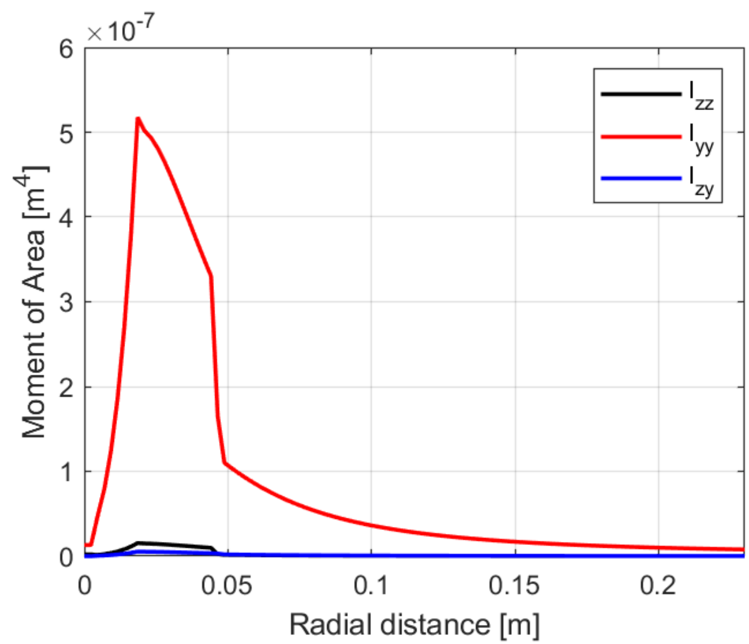
R: Blade Radius
r: radial distance

Structural Performance Prediction

Airfoil sections were centered at their center of area to make stress calculations easier.



Section Areas

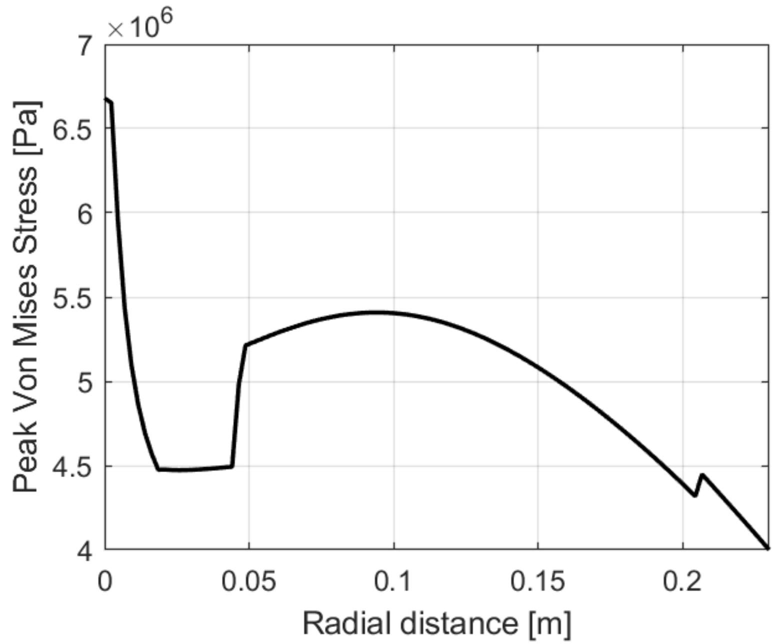


Moment of Area

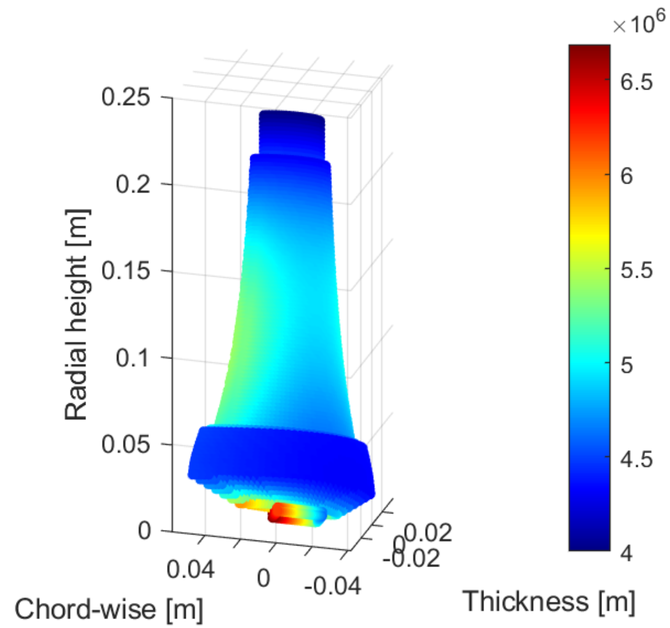
First and Second Moments of Area are calculated using a polygon approximation method [18]

Structural Performance Prediction

Peak Von Mises stress: $\sigma_x = -\left(\frac{M_y I_z - M_z I_{zy}}{I_z I_y - {I_{zy}}^2}\right) z - \left(\frac{M_z I_y - M_y I_{zy}}{I_z I_y - {I_{zy}}^2}\right) y$ [17]



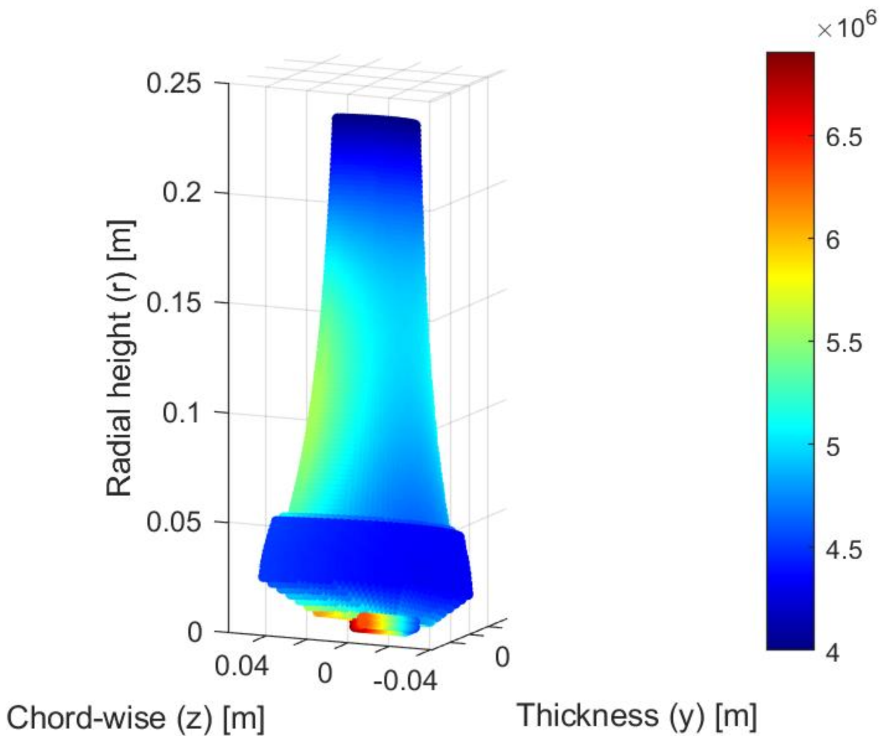
Section Areas

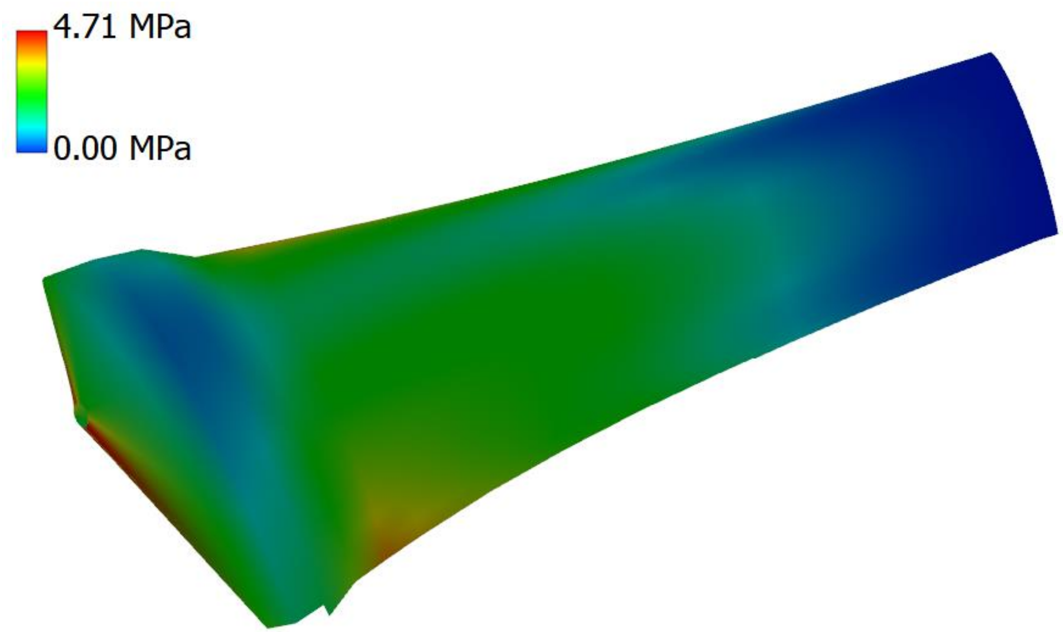


3D visualisation

Without switching to SG-6040 - maximum stress: 10.4 MPa
Shear stress on epoxy: 110kPa. Safety factor: 45.4 (5MPa shear strength [19])
Birch Plywood UTS: 34 MPa [19] - Minimum safety factor: 5.1

Structural Performance Prediction

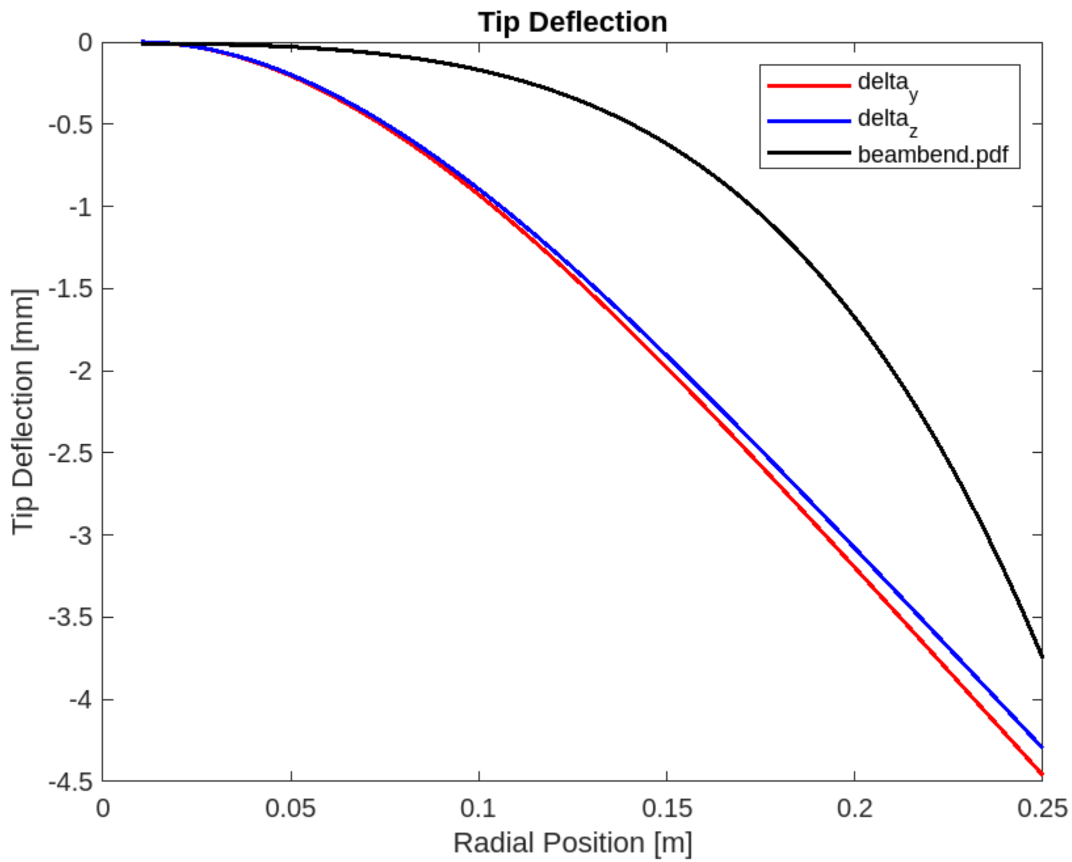




QBlade v2.0.8.6 Load Analysis

Structural Performance Prediction

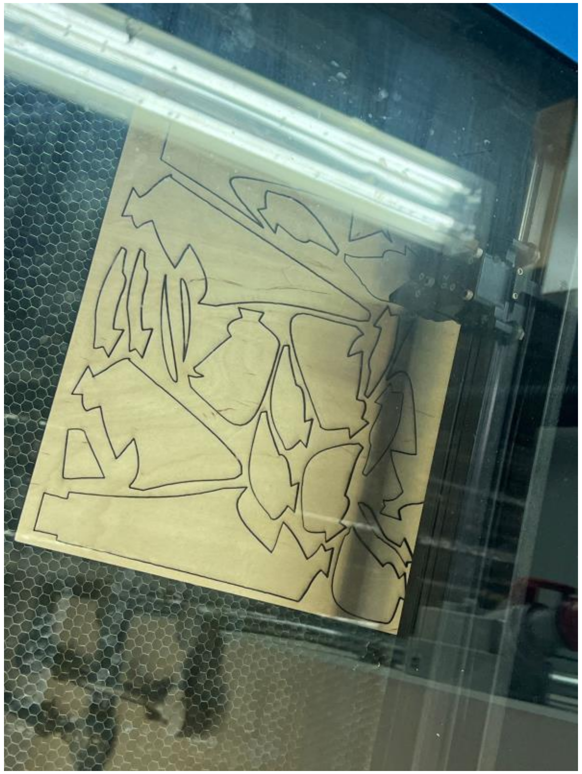
Tip Analysis:



[20, 21, 22]

Prototype Manufacturing Methodology

- Step 1: Laser cut individual plywood sections as required (note that laser may need to be used twice to fully cut through the wood)



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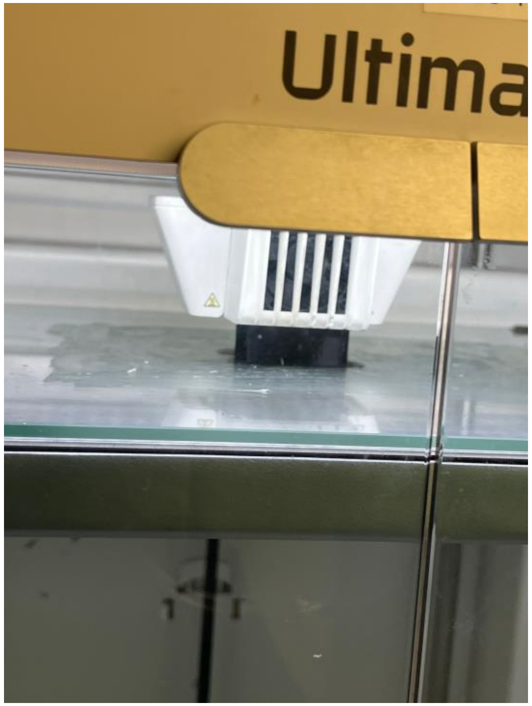
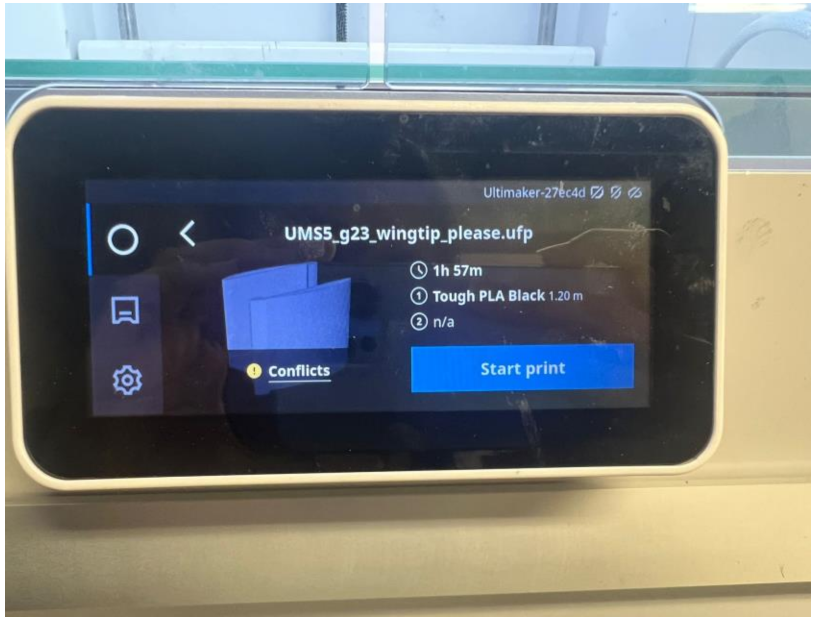
Prototype Manufacturing Methodology

Step 2: 3D print the wingtips with the winglets





Prototype Manufacturing Methodology

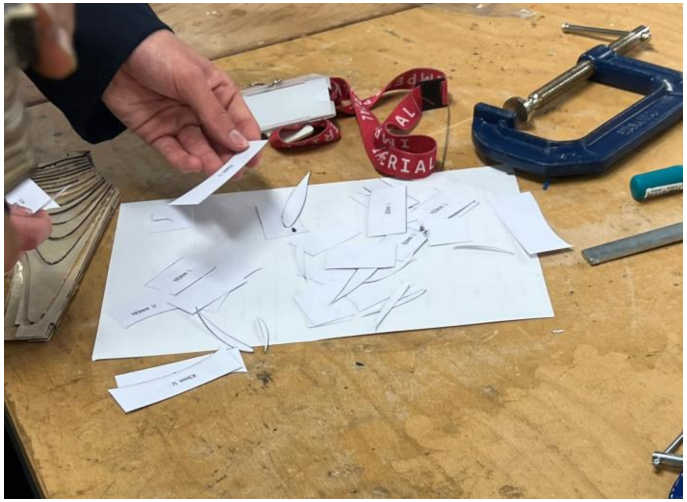
Step 3: Glue plywood sections together and clamp them to ensure a strong bond. Allow them to dry.

Step 4: File it down to the expected geometry.

Prototype Manufacturing Methodology

Step 5: Print paper aerofoil sections to verify the geometry is as intended and modify if needed (through sanding)

Step 6: Attach 3D printed tips to the blade via the tab/slot using epoxy. Let it dry the necessary amount of time.

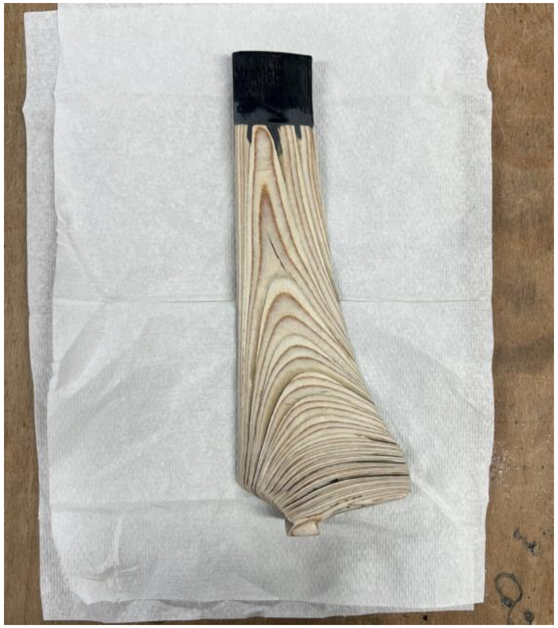


Prototype Manufacturing Methodology

Step 7: Ensure that the dovetail fits into the turbine hub. If not, sand it down in order to match the requirements.

Prototype Manufacturing Methodology

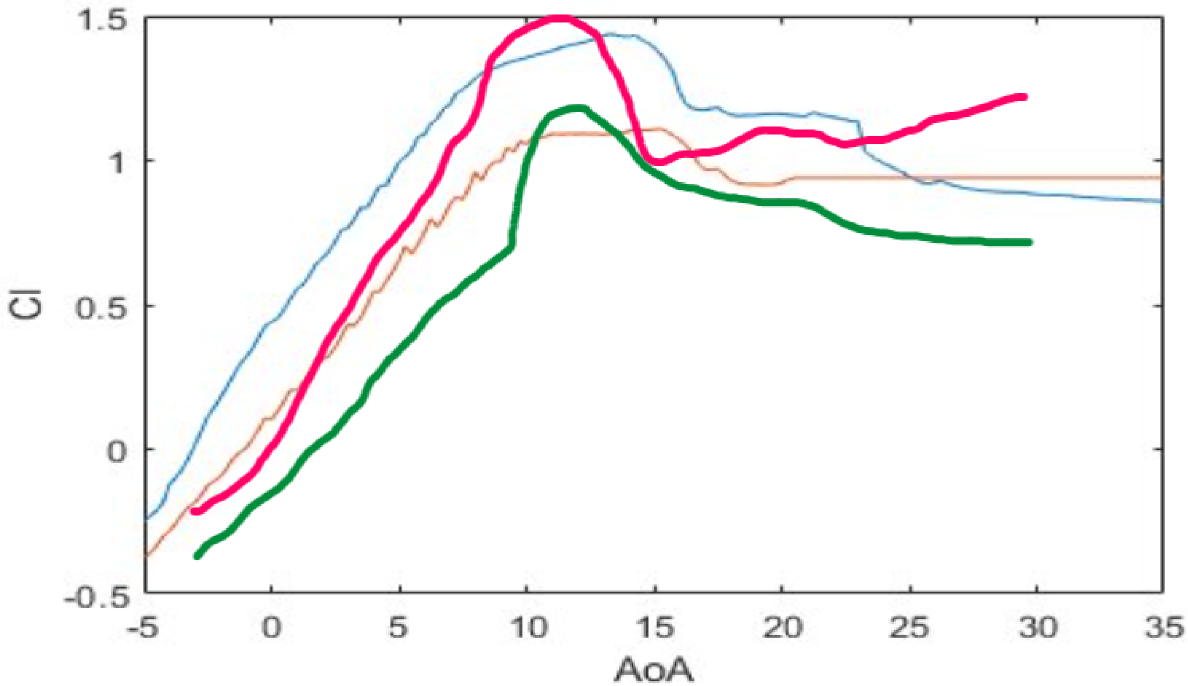
Step 8: Clean each blade using damp paper towel. Apply varnish to each blade. To minimise bubbles on the surface: apply very thin layers. Let it dry for thirty minutes. Repeat twice more.



Conclusion

- Predicted Power: 44W
- Used SG6040 & SG6043 for our two-blade design. Combining 3D-printed winglets with a laser-cut plywood body.
- Key challenges included shaping the dovetail and balancing our blades.
- Total cost: £25

Appendix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AoA

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